

Supersymmetry and New Physics at $\gamma\gamma$ colliders*

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In this contribution we present a discussion of some aspects of the capabilities of a photon collider to probe physics beyond the standard model. I will take a few examples from Higgs physics, supersymmetry, extra dimensional theories as well as unparticles, pointing out the special rôle that a photon collider can play in each case.

1 Introduction

I have been asked to discuss new physics at the $\gamma\gamma$ collider [1]. In general, new physics can be discussed in two different ways:

- a) In the framework of specific models proposed with a view to cure one or more of the ills of the SM, some well motivated and some speculative. Supersymmetry (SUSY), extra dimensional models (ED), little higgs models, noncommutative theories, unparticles etc. are some examples.
- b) The second is to look at the effect on different aspects of phenomenology at a $\gamma\gamma$ collider such as jet production, $t\bar{t}$ production or Higgs physics studies etc., in a model independent manner.

In this contribution I will pick some combination of the two above mentioned strategies as well as that of the topics. I will mainly concentrate on physics of the sparticles and (BSM) Higgs at the $\gamma\gamma$ colliders, trying to identify where the $\gamma\gamma$ collider has a distinct advantage in terms of adding clarity to a particular study, and/or increasing the coverage in (SUSY) model parameter space as well as the reach in masses, compared to the e^+e^- option. I will also include some discussion of new physics such as extra dimensional theories or more speculative case of unparticles in the context of $\gamma\gamma$ colliders.

The two special features of the PLC of great help in this are: the very accurate measurements ($\sim 2\%$) of the $\Gamma_{\gamma\gamma}$ decay width for the Higgs boson into two photons and good control on the polarisation of the initial photon beams.

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2 SUSY: LHC Wedge, LEP hole and LHC/ILC

It is necessary to summarise the LHC and LHC/ILC possibilities for SUSY studies and searches [2], before turning to a discussion of the possibilities at the PLC. Recall that, the sparticle mass spectrum depends on the mechanism responsible for SUSY breaking and can vary widely, *but* the sparticle spins and couplings are predicted unambiguously. To establish SUSY with the help of the two colliders LHC and ILC, we need to find the sparticles, measure their masses, spins and couplings. Another thing is to note that for $\tilde{\chi}^\pm, \tilde{\chi}_1^0$ as well as the supersymmetric partners of the third generation of the quarks/leptons, the masses as well as the couplings, can depend on the SUSY breaking mechanism and parameters. The LHC will be able to 'see' the strongly interacting sparticles if the SUSY scale is TeV. If the sparticle mass is within the kinematic reach of the ILC, we will be able to make accurate mass measurements and also can make clean spin determination. In this situation the ILC can even help us determine the SUSY model parameters and hence the SUSY breaking mechanism as has been summarised in the SPA program [3]. In spite of this very impressive and exhaustive coverage of SUSY by the LHC and the ILC in e^+e^- mode, there are a few 'holes' in the SUSY parameter space. In the so called LHC wedge [4], $\tan\beta \simeq 4 - 10$, $M_A, M_H > 200-250$ GeV, only the light Higgs h of SUSY will be observable at the LHC and the H/A will not be visible at the first generation ILC. In case of CP violating MSSM also, there exists a 'hole' in the $\tan\beta$ - m_{H^\pm} plane, for low $\tan\beta \lesssim 3 - 5$. This corresponds to three neutral higgses $\phi_i, i = 1 - 3$, which may not be CP eigenstates, in the mass range $m_{\phi_1} < 50, 100 < m_{\phi_2} < 110$ and $130 < m_{\phi_3} < 180$. This region can not be ruled out by LEP searches and where the LHC also may not have reach [5]. The $\gamma\gamma$ collider (PLC), can indeed offer unique possibilities in this case. Further, discovery of any charged scalar would uniquely signal physics beyond the SM (BSM). In the following we will present examples of the special role that the PLC can play in this context.

3 Increased reach for new particle searches at the PLC

As already mentioned charged Higgs, for that matter, any charged scalar will be a signal of BSM physics beyond any doubt. The production cross-sections of such scalars are enhanced in $\gamma\gamma$ collisions, compared to that in e^+e^- collisions, by a factor of Q_S^2 , where Q_S is the electromagnetic charge of the scalar S. This is relevant, for example, in the little higgs models, which have doubly charged scalars. Even for the singly charged scalars, the dependence of the pair production cross-section on the original e^\pm beam energy depends on the polarisation combination of the two beams and can be used to increase the mass reach. Right panel in Figure 1, taken from Ref. [6], showing this polarisation dependence as function of $m_{H^{++}}$ illustrates this. In fact the right hand side panel of the same figure, taken from Ref. [7], showing the cross-section for scalar quark production, both in e^+e^- collisions and at the $\gamma\gamma$ collider, as a function of the scalar quark mass, directly illustrates how one can increase the reach in the charged scalar sector over the LC mode, at a 1 TeV LC.

Above discussion clearly highlights the advantage offered by a PLC in case of charged scalars with a clear increase in the range of scalar masses that can be probed with a given e^+/e^- beam energy. An increase in the range (by about a factor of 1.6) in the reach in the mass of the heavy Higgs of SUSY (H/A), due to the single Higgs production that is possible at the PLC, compared to that in pair production in e^+e^- colliders, had also been noted in the context of MSSM higgs boson searches. This in fact can fill the LHC wedge region of the MSSM parameter

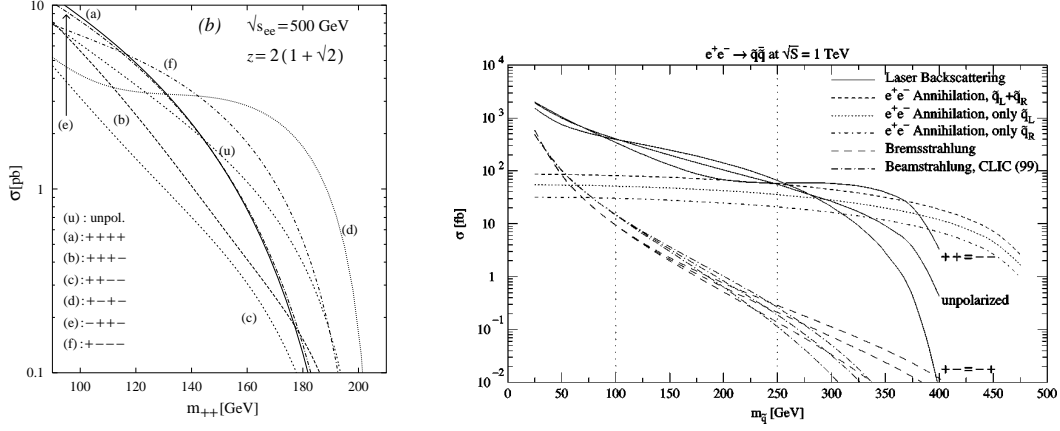


Figure 1: Beam polarisation dependence of the production cross-section charged scalars for doubly charged scalars(left panel) [6] and for squarks (right panel) [7] as a function of the mass.

space [8]. In addition to this, the PLC, in the $e\gamma$ option can increase the range of $m_{\tilde{e}_R}$ mass if the mass difference between the \tilde{e}_R and $\tilde{\chi}_1^0$ is large. At an $e\gamma$ collider, the $e\gamma \rightarrow \tilde{e}_R \tilde{\chi}_1^\pm$ process has reach up to $m_{\tilde{e}_R} + m_{\tilde{\chi}_1^0} < 0.9\sqrt{s_{ee}}$, where as at an e^+e^- collider the reach is $0.5\sqrt{s_{ee}}$. This has already been discussed in other talks at this conference [9]. Further, this is possible without the need of a polarised initial beam.

4 Better measurement of SUSY parameters

Not just for the charged scalars but also for the new charged fermions, like $\tilde{\chi}_1^\pm$, pair production in $\gamma\gamma$ collisions, can afford a good measurement of the B.R. ($\tilde{\chi}_1^\pm \rightarrow W \tilde{\chi}_1^0$) and can increase the accuracy of $\tan\beta$ determination in the SPA fit by over a factor 2–3 [9, 10], for a MSSM point with parameter choice very similar to that for SPS 1a.

In fact determination of $\tan\beta$ at an e^+e^- collider is a particularly notorious for the lack of accuracy at large $\tan\beta$ in the process $\tilde{\chi}^+ \tilde{\chi}^-, \tilde{\chi}_j^0 \tilde{\chi}_i^0$ mainly due to the fact that the observable involves $\cos 2\beta$ [11]. $\gamma\gamma \rightarrow \tau^+ \tau^- \phi \rightarrow \tau^+ \tau^- b \bar{b}$, on the other hand offers a very good measurement of $\tan\beta$. Results of a phenomenological calculation [12], show that at $\tan\beta = 30$ it may be possible to have $\Delta \tan\beta = 0.9\text{--}1.3$, to be contrasted with an accuracy of about 10–12 [11] at the e^+e^- option. It is clear that this process has the potential to help enormously in SUSY parameter determination. However, this needs to be backed up by detailed simulations.

5 Higgs physics and the PLC

An accurate measurement of $\Gamma(\phi \rightarrow \gamma\gamma)$, determination of the CP property of the Higgs, as well as measurement of CP mixing in case of CP violation, are the three important ways in which a PLC can make value addition compared to an e^+e^- collider. Many of these features, apart from the CP violation in the Higgs sector, both in the context of a particular model (SUSY) and in a model independent approach were already described in different talks [9, 13] at this conference.

Almost any new physics, may it be SUSY, with and without CP violation [14, 15, 16, 17] or 2-higgs doublet model [18] will in fact affect the $\gamma\gamma$ -Higgs couplings and hence the width. In the CPV MSSM or MSSM with non universal gaugino masses, these effects can be significant, yet being consistent with the current limits on all the sparticle masses.

A unique feature of a PLC is that the two photons can form a $J_z = 0$ state with both even and odd CP. As a result, unlike the gauge boson fusion mode which contributes mainly in the e^+e^- mode to the production, the PLC has a similar level of sensitivity for both the CP-odd and CP-even components of a CP-mixed state:

$$\text{CP-even} : \epsilon_1 \cdot \epsilon_2 = -(1 + \lambda_1 \lambda_2)/2, \quad \text{CP-odd} : [\epsilon_1 \times \epsilon_2] \cdot k_\gamma = \omega_\gamma i \lambda_1 (1 + \lambda_1 \lambda_2)/2, \quad (1)$$

ω_i and λ_i denoting the energies and helicities of the two photons respectively; the helicity of the system is equal to $\lambda_1 - \lambda_2$. This contrasts the e^+e^- case, where it is possible to discriminate between CP-even and CP-odd particles but may be difficult to detect small CP-violation effects for a dominantly CP-even Higgs boson [5, 19].

In this talk I should like to concentrate on the CP violation and anomalous hVV couplings in the Higgs sector pointing out the role that the PLC can play in their study, after briefly mentioning the prominent issues in the first two topics.

5.1 LHC-wedge

At large $\tan\beta$ region, the dominant decay mode of the H/A is into the $b\bar{b}$ channel, where the $b\bar{b}$ background can be controlled by a judicious choice of photon polarisation. H/A separation can be achieved by choosing polarisation vectors of the two photons to be perpendicular and parallel; but this has implications for the QED $q\bar{q}$ background as well. Results of a detailed simulation [20], which were already discussed at this conference, show that for a light higgs it would be possible to measure the $\gamma\gamma$ rates accurate to $\simeq 2\%$ whereas for H/A measurement precision would be somewhat worse : $\sim 11\%-21\%$. In fact in these region the Supersymmetric decay of the H/A into $\tilde{\chi}^\pm, \tilde{\chi}_l^0$ pairs can also be used [8].

5.2 CP properties and CP violation in the Higgs sector

In the MSSM the properties of the Higgs sector, at the tree level, are determined in terms of two parameters $\tan\beta$ and μ . If some of the SUSY parameters have nonzero phases, then the Higgs sector can have loop generated CP violation, even with a CP conserving tree level scalar potential [21]. Recall the existence of the 'LEP-hole' mentioned earlier. Effect of this CP violation on the masses and the coupling of the Higgses in this parameter range, can also affect the LHC reach and part of the 'hole' remains [5], even after the recovery of some part of the parameter space through the decay chain $t \rightarrow bH^+ \rightarrow bWh \rightarrow bWb\bar{b}$ [22].

A PLC will be able to produce such a neutral Higgs in all cases; independent of whether it is a state with even/odd or indeterminate CP parity. For the PLC, one can form three polarization asymmetries in terms of helicity amplitudes which give a clear measure of CP mixing [23]. Note however that these require linearly polarised photons in addition to the circular polarisation. With circular beam polarization almost mass degenerate (CP-odd) A and (CP-even) H of the MSSM may be separated [8, 20]. In addition, one can use information on the decay products of WW, ZZ [24]. Further, Higgs contribution to $\gamma\gamma \rightarrow f\bar{f}$ can give nontrivial information on the CP mixing [25, 26, 27, 28, 29, 30, 5].

- $f\bar{f}$ final state.

The process receives contributions from the s -channel Higgs exchange and the t -channel QED diagram. It is possible to determine the CP mixing, if present, by using the polarisation of the initial state γ or that of the fermions into which the ϕ_i decays. In MSSM the CP-even H and the CP-odd A are degenerate. In the situation that the mass difference between the two is less than the sum of their widths, a coupled channel analysis technique [31] has to be used. The authors of Refs. [28] and [29] explore the use of beam polarisation and final state fermion polarisation to analyse this situation whereas the use of decay fermion polarisation for determination of the Higgs CP property for a generic choice of the MSSM parameters is explored in Ref. [30].

The most general couplings of a Higgs to $f\bar{f}$ and $\gamma\gamma$ can be written in a model independent way, accounting for possible CP violation, as [26, 27]:

$$\begin{aligned}\mathcal{V}_{f\bar{f}\phi} &= -ie\frac{m_f}{M_W}(S_f + i\gamma_5 P_f), \\ \mathcal{V}_{\gamma\gamma\phi} &= \frac{-i\sqrt{s}\alpha}{4\pi} \left[S_\gamma(s) \left(\epsilon_1 \cdot \epsilon_2 - \frac{2}{s}(\epsilon_1 \cdot k_2)(\epsilon_2 \cdot k_1) \right) - P_\gamma(s) \frac{2}{s} \epsilon_{\mu\nu\alpha\beta} \epsilon_1^\mu \epsilon_2^\nu k_1^\alpha k_2^\beta \right].\end{aligned}$$

When we consider this in the context of a particular model then the form-factors, $\{S_f, P_f, S_\gamma, P_\gamma\}$ depend upon model parameters. For example, for the CP violating MSSM these depend on m_{H^\pm} , $\tan\beta$, μ , $A_{t,b,\tau}$, $\Phi_{t,b,\tau}$, $M_{\tilde{q}}$, $M_{\tilde{l}}$ etc. The model independent case and the specific case of

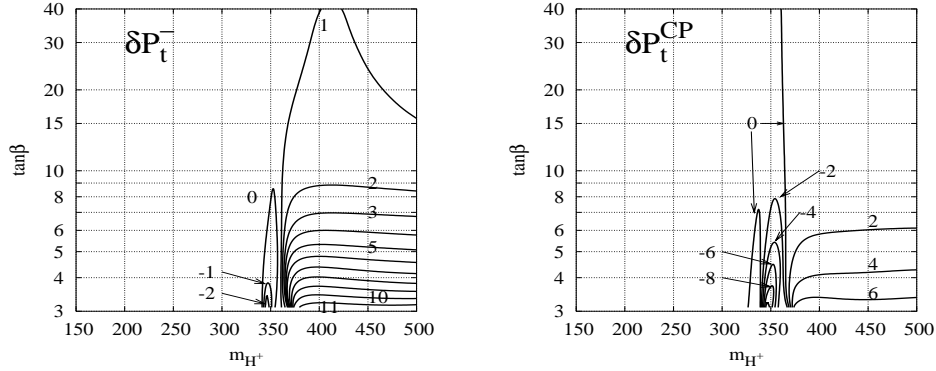


Figure 2: Expected values (in %) of δP_t^- and δP_t^{CP} for the top quarks produced in the process, $\gamma\gamma \rightarrow t\bar{t}$, including the s -channel Higgs exchange contribution, in the CPV MSSM, in the CPX scenario, in the m_H^+ - $\tan\beta$ plane [30]

CP violating SUSY are analysed in Refs. [26, 27] and [30] respectively. The helicity amplitude for the production will in general involve CP even combinations such as $S_f \Re(S_\gamma)(\text{viz. } x_i)$ as well as CP odd-combinations such as $S_f \Im(P_\gamma)(\text{viz. } y_i)$. Note that the QED background is P , CP and chirality conserving. Higgs exchange diagram violates these symmetries. This means that in the presence of the Higgs, existence of chirality flipping interaction imply nonzero values of the various $\{x_i, y_j\}$ which in turn means that the fermion-polarisation carries a footprint of the Higgs contribution as well as any CP violation in the $\phi\gamma\gamma$ and $\phi f\bar{f}$ couplings. It is also very gratifying that the heavier fermions t, τ which have the largest $\phi f\bar{f}$ coupling are also the

fermions whose polarisation is amenable to experimental measurements. The polarisation of the initial state γ can be controlled by adjusting the initial laser and the e polarisation. The ϕ contribution is enhanced using the combination $\lambda_e \times \lambda_l = -1$. One can construct observables, with unpolarised and polarised laser and e beams in terms of expected fermion polarisation: P_f^U being the expected one for unpolarised initial states and P_f^{++}, P_f^{--} being the observables with polarised beams. Here $+/-$ in the (double) superscripts refer to the polarisation of the e, λ_e . P_f^{++}, P_f^{--} are nonzero even for the QED diagrams alone, but the P invariance of QED implies $P_f^{++} = -P_f^{--}$. Hence a nonzero value for $P_f^{++} + P_f^{--}$ will clearly indicate parity violation. In case of C invariance this then is also CP violating. Thus P_f^U and $\delta P_f^{CP} = P_f^{++} + P_f^{--}$ are both probes of CP violating contribution. Further, P_f^{++} is modified by the Higgs contribution such that $P_f^{++} - (P_f^{++})^{QED} \neq 0$ even if ϕ is CP eigenstate. Hence, $\delta P_f^+ = P_f^{++} - (P_f^{++})^{QED}$ and $\delta P_f^- = P_f^{--} - (P_f^{--})^{QED}$ are both probes of chirality flipping interactions. Figure 2, taken from Ref. [30], shows the values for δP_t^- and δP_t^{CP} , expected in the CP-violating MSSM, in the $m_H^+ - \tan\beta$ plane, for the CPX scenario [21], in the left and the right panel respectively. A

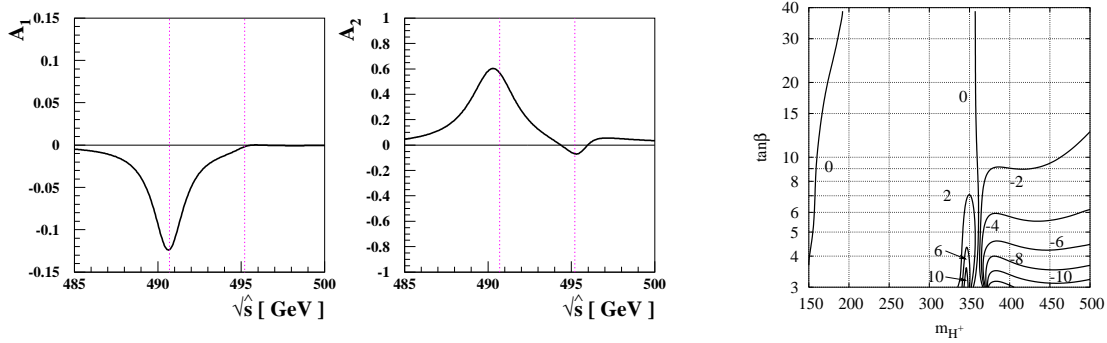


Figure 3: CP violating asymmetries constructed out of different combination of cross-sections with final state t helicity and initial state photon helicity for top quarks produced in the process, $\gamma\gamma \rightarrow t\bar{t}$, including the s -channel Higgs exchange contribution, in the degenerate ϕ_2/ϕ_3 case in CPV MSSM as a function of the $\gamma\gamma$ centre of mass energy (two left panels) [28] and the mixed lepton charge-photon helicity asymmetry (in%) for the generic case in the CPX scenario, in the $m_H^+ - \tan\beta$ plane with a choice of e^+e^- beam energy to maximise the asymmetries (right panel) [30].

similar calculation of the expected τ polarisation indicates that the two fermion polarisation offer coverage in the complementary regions of this parameter space and part of the 'LEP'-hole, which can not be covered at the LHC, can in fact be covered by these measurements. Note that the ILC can provide part coverage of the region through production of other Higgs bosons, but $\gamma\gamma$ collisions and/or production in the decay of the charged higgs [22], remain the only two modes for the light neutral higgs, in this left over region of the 'LEP-hole'.

The expected values of the various observables presented in the Figure 2 and the rightmost panel of 3, are for a value of the common CP violating phase $\Phi = 90^\circ$. and the beam energy is adjusted for each point in the scan such that the peak of the photon spectrum matches with

scaled mass $m_\phi/\sqrt{s_{\gamma\gamma}}$, m_ϕ being the average mass of the two states which may be close in mass. Nowhere in this range of the parameters are such that the two states are extremely degenerate, and hence a coupled channel analysis is not required. We see that even in this case, the size of the expected asymmetries is not too small. Thus in a generic case of CPV MSSM, the PLC can probe this CP-mixing in the Higgs sector. In case of extreme degeneracy of the two states, the expected polarisation asymmetries for both the fermion final states containing τ and t , are enhanced resonantly and the observability is increased even more. The left two panels of Figure 3 taken from Ref. [28] show two such CP violating asymmetries constructed out of combination of cross-sections with different helicities for the initial state photons and final state quarks, as a function of $\sqrt{s_{\gamma\gamma}}$, with model parameter values chosen to maximise the effect.

Since the top quark decays before it hadronises, the decay products retain the top quark spin information. In fact, the decay lepton angular distribution is a particularly good probe of this polarisation due to the independence of the correlation between the polarisation and the angular distribution and any anomalous tbW vertex [32]. The above mentioned polarisation asymmetries translate into 'mixed beam polarisation-lepton charge asymmetry' constructed out of cross-sections with different photon helicity combinations as in Ref. [26], but for values of the form factors $S_f, P_f, S_\gamma, P_\gamma$, calculated in the CPX scenario as a function of the MSSM parameters $\tan\beta$ - m_{H^\pm} plane. These, taken from Ref. [30] are shown in the rightmost panel of the Figure 3.

• 2HDM and WW/ZZ final states at a PLC

As mentioned earlier, CP violation in the Higgs sector has also been studied in the context of a two Higgs doublet model and the possibility of determining the CP violating phase through the kinematic distribution of the decay products of the W and the Z [24], with a realistic photon spectra has been investigated. The phase Φ_{CP} and the relative strength of the ϕVV coupling relative to that in the SM can be measured to about $\lesssim 0.02$ – 0.05 depending on the mass of the Higgs.. The errors are computed, assuming the SM value of 0 and 1 respectively for the two. The interesting part of this study is the fact that the two photon width, its phase and the relative normalisation of both samples, are all allowed to vary in the fit. The former, which is available only at a PLC, is seen to impact the results significantly.

In fact in the $e\gamma$ option the photon collider offers also a unique possibility of determining accurately the hWW anomalous coupling. The accuracy of determination of this coupling in the e^+e^- option is limited due to the big background from the ZZh contribution to the same final state. This does not require polarised beams either [33].

5.3 Higgs self coupling and the $\gamma\gamma$ collider

The ILC in the e^+e^- mode offers only a very limited information on the trilinear hhh coupling [2, 34]. This information can be obtained through a study of Higgs pair production at a $\gamma\gamma$ collider and is shown to be a good probe of hhh couplings and comparable perhaps to other probes at the LHC and the ILC. Recently, the modification of the hhh coupling in the framework of a general two Higgs doublet models was addressed in a couple of analyses [35, 36, 37]. If the modification of the hhh coupling is due to new particles in the spectrum, then it will also modify $h\gamma\gamma$ as well the $\gamma\gamma hh$ coupling. So in the framework of a two higgs doublet model they calculate the net change in the cross-section $\gamma\gamma \rightarrow hh$ and show that the sensitivities possible at the PLC can indeed test these models.

6 Extra Dimensional models and the PLC

In the context of models with TeV scale gravity; ie. models with extra dimensions, the $\gamma\gamma$ production of all the matter and gauge boson fields is altered substantially. The extra dimensions can be probed in the dijet final state [38], through the gauge boson couplings to a pair of photons [39], in the production of a $t\bar{t}$ pair [40] as well as in the $e\gamma$ mode [41], up to a scale comparable and/or somewhat higher level, compared to the LC option. However, all these calculations have been done at the theorists level and an evaluation of the net gain due to PLC, when a realistic photon spectrum is used, is not available.

7 Unparticles and the PLC

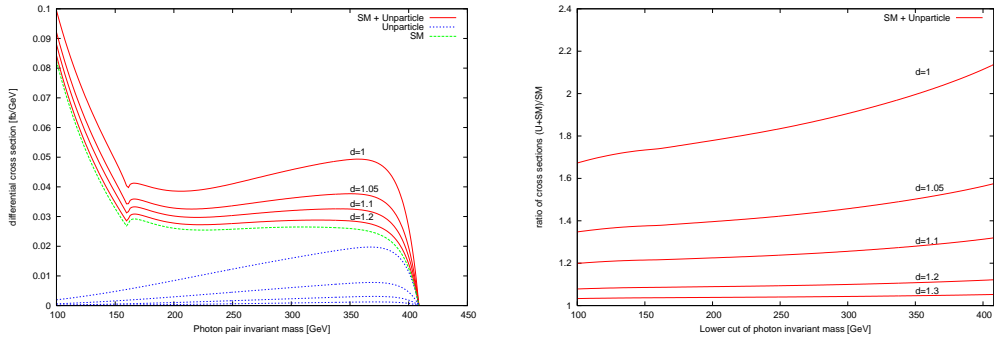


Figure 4: The $\gamma\gamma$ invariant mass distribution for a 500 GeV machine showing the effect of scaling dimension of the unparticles(left panel) and the values of $\sigma_U + \sigma_{SM}/\sigma_{SM}$ as a function of $\gamma\gamma$ centre of mass energy(right panel) [42].

Along with the very well motivated physics beyond the SM like Supersymmetry and extra dimensions, the PLC can also probe speculative physics like unparticles. Among the different discussions that exist, I am going to give only one example taken from [42], where they consider the effect of unparticles on the process $\gamma\gamma \rightarrow \gamma\gamma$, which can be studied at a photon collider. In these theories a hidden conformal sector provides “unparticle” which couples to the Standard Model sector through higher dimensional operators in low energy effective theory. If one focuses on operators which involve unparticle, the Higgs doublet and the gauge bosons, after the Electroweak Symmetry breaking, a mixing between unparticle and Higgs boson ensues. In turn this can cause sizable shifts for the couplings between Higgs boson and a pair of photons [43]. Since the process proceeds in the SM only at loop level, it has a great potential to probe new physics. The authors of Ref. [42] show that $\gamma\gamma$ collider in this case can be sensitive to a scale of 5 TeV for $\sqrt{s} = 500$ GeV. The plot in the left panel of Figure 4 taken from this reference, shows the cross-section as a function of $\gamma\gamma$ invariant mass. The structure in this distribution reflects the scaling dimension of unparticle. The second plot (right panel) in Figure 4 shows ratio of $\sigma_U + \sigma_{SM}/\sigma_{SM}$.

8 Conclusions

Thus a PLC can play an important and unique role in many ways in probing BSM physics. Loop effects on $\gamma\gamma$ processes and couplings can probe it indirectly. Further, it can affect search prospects of new charged scalars, a sure harbinger of New Physics, by providing comparable reach, if not more, as the e^+e^- option for a TeV energy LC. Polarisation dependence of the photon spectrum and cross-section can play an important role. $\Delta\beta \simeq 1$ at large $\tan\beta$ can be achieved using $\tau\tau$ fusion. There are major gains for the SUSY Higgs sector as it provides reach for H/A in regions where LHC does not have any. The s channel production increases reach in the mass of neutral Higgses by a factor ~ 1.6 due to single production that is possible. Advantages of a $\gamma\gamma$ collider are even more if CP violation is present in the Higgs sector. The polarisation asymmetries constructed using initial state photon polarisation and final state fermion polarisations, can be a very good probe of the CP violation in the Higgs sector. The H/A contribution can be probed therefore through mixed polarisation-charge asymmetries, i.e asymmetries in initial state polarisation and final state lepton charge. If CP violation makes the lightest higgs dominantly pseduoscalar and hence 'invisible' at LEP/ILC/LHC, then $\gamma\gamma$ collider is the only place it can be produced directly. The PLC is capable of probing new physics such as extra dimension through production of dijets, top pairs, gauge bosons etc. in $\gamma\gamma$ collisions.

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